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Final Technical Report
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Collisionless Dynamics of the Magnetosphere

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Summary

This research was motivated to understand the generation and transport of energetic particles found in laboratory, astrophysical and space plasmas. In particular, we studied the collisionless acceleration and transport of electrons driven by solar variability and the nonlinear dynamics of strong interchange instabilities. We created an "artificial radiation belt" in the laboratory, allowing the creation and study of intense interchange instabilities. Our investigations combined laboratory experimentation, computer simulation, and plasma theory. Recent measurements confirmed our self-consistent model for the nonlinear evolution of the interchange instability of hot plasma confined by dipolar magnetic fields. Additionally, we have discovered a mechanism to reduce the intensity of interchange instabilities by the application of high-frequency electromagnetic waves. Building on the knowledge gained through this research, we are conducting new investigations using support from the DOE/NSF partnership in basic plasma science. This work aims to understand the nonlinear dynamics of strong interchange instabilities in rotating dipole-confined plasma and to observe, for the first time in a single experiment, interchange instabilities excited by magnetic curvature and driven plasma convection.

Our research program has made reached important conclusions. These are:

1. Temporal dynamics of charged radiation trapped in a magnetic dipole and associated with sudden and strong nonlinear transport can be understood by using guiding center drift Hamiltonian [Warren and Mauel, 1995a],

2. The *instantaneous* local flux to a satellite (or a probe) requires a kinetic theory even though the *average* transport induced by fluctuations in a dipole can be modeled by a quaslinear theory [Warren and Mauel, 1995b],

3. Nonlinear interchange instabilities in a magnetic dipole can create long-lived structures (that we have called "phase-space holes" or "vacuum bubbles") [Mauel, 1997],

4. Self-consistent, nonlinear computer simulation of interchange instability of plasma within a dipole magnetic field can accurately predict many key laboratory measurements,

5. Higher-frequency, bounce-resonant fluctuations can *suppress* the long-lived plasma structures created by interchange instability, and

6. Current flow along magnetic field lines is an important in the drive for solar storms [Boozer, 1999].

Our program has addressed all topics originally proposed for study, and they either have been published or will be published within archival journals.

This research has also had an essential impact on Columbia University's academic activities in laboratory and space physics. During the past few years, this research program has supported the education of five graduate students and six undergraduate students. Finally, our research uncovered entirely new topics of investigation that are the subject of new and separately funded research activities.

In the following, we present a brief summary of the most recent work. We describe (1) the observation of the global structure of interchange instabilities and the verification of our self-consistent, nonlinear model, (2) the observation of interchange mode suppression with applied RF waves, and (3) the identification of the role of helicity and parallel current constraints on coronal heating.

1. GLOBAL STRUCTURE OF INTERCHANGE INSTABILITY

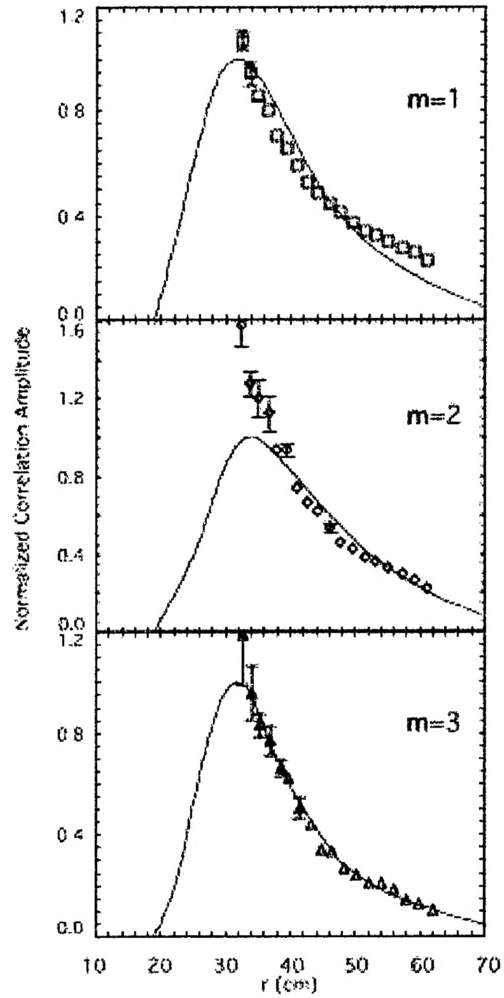
The nonlinear dynamics of strong interchange instabilities concerns fundamental phenomenon occurring in a variety of natural and artificial situations. These include gravitational Rayleigh-Taylor (GRT) instability found in the F-layer of the ionosphere, the rotationally-driven interchange instability of the Io plasma-torus of Jupiter, and the hot-particle curvature-driven interchange instabilities found in magnetized laboratory plasma experiments.

We discovered a laboratory technique to produce intense interchange instabilities in a dipole-confined plasma. In the experiment, a population of energetic electrons are produced by an ECRH plasma source and confined by a simple mechanically-supported dipole electromagnet. The energetic electrons excite a sequence of quasi-periodic bursts of resonant drift instabilities that are relatively easy to measure and to study. These curvature-driven interchange instabilities saturate with complex collisionless processes that include strongly nonlinear frequency-chirping [Warren and Mauel, 1995a]. By using movable probes and computer simulation, we have shown that the observed frequency-chirping corresponds to the inward propagation of vacuum "bubbles". Near saturation, the instability modulates completely the local energetic particle flux implying the observed phase-space "bubbles" are deep. Because of the strong magnetic field in our experiment, the plasma dynamics can be understood as motion of charged flux-tubes. We have demonstrated good agreement between nonlinear self-consistent simulations and experimental observations [Mauel, 1997].

In our previous laboratory work, we developed techniques to form and observe an "artificial radiation belt", measured collisionless fluctuation-induced transport, and developed nonlinear models to interpret the experimental results. Most recently, we have measured the radial, azimuthal and field-line mode structures of interchange instabilities excited by energetic electrons confined by a magnetic dipole. The mode structure is determined via a correlation analysis of movable high-impedance floating potential probes located at various positions within the plasma. The hot electron population, produced by electron cyclotron resonance heating, becomes unstable to HEI instabilities that saturate nonlinearly with a complex and time-varying frequency spectrum. However, we find the mode structure itself does not evolve significantly in time and seems to be determined by azimuthal mode number. We have compared these measurements to our self-consistent nonlinear particle simulation and significantly corroborate the experimental findings, reproducing temporal, radial and azimuthal structure as well as showing dependence on boundary conditions [Levitt, *et al.*2001].

The global mode structure was measured with five movable high impedance floating potential probes are located throughout the vacuum chamber. Since the locations of these probes are known, the mode structure can be reconstructed from cross-

correlation of the signals of particular pairs of probes. When the probes are located at the same magnetic flux, the propagating interchange mode's azimthal mode number, *m*, causes a phase-difference. Typically, several azimuthal modes co-exist. When the probes are located at different radii, the radial mode structure (for each *m*) can be measured.



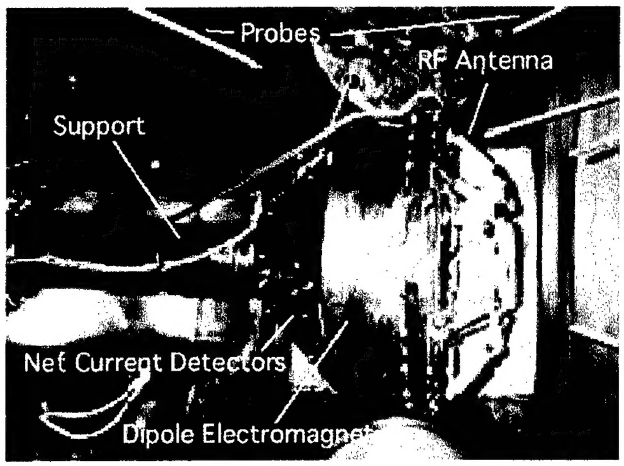
The radial profile along the equatorial plane of the phase of the two-probe correlation function is shown in the figure to the right. In this figure, the azimuthal phase differences have been removed. The three lowest *m* numbers were examined at three different times with each radial location representing averages of several shots. These show no apparent time dependence in the phase. By the same token, there is no change in the phase with radius. The interchange modes have a broad "rigid-rotor" radial structure.

The smooth profiles underneath represent the predictions from our nonlinear simulation. Very good agreement is seen.

2. Suppression of Interchange Instabilities with Applied RF Waves

We have made new observations of the impact of bounce-resonant electric fields applied to plasma exhibiting strong interchange instabilities. When monochromatic electric fields are applied near the bounce-frequency of the resonant energetic electrons, the saturation behaviors of the interchange instability dramatically change. For applied fields of sufficient intensity and pulse-length, we observe (1) the suppression of coherent interchange fluctuations, (2) a reduction of radial transport of energetic electrons, and (3) a steepening of the density gradient of confined plasma. Possible explanations include breaking the second adiabatic invariant so as to fill "phase-space holes" and enhancing the plasma density so as to increase the stabilizing polarization current.

Interchange instabilities excited by energetic electrons trapped by a magnetic dipole nonlinearly saturate with complex, coherent spectral characteristics [Warren and Mauel, 1995a]. As already discussed, multiple azimuthal modes co-exist, propagating with frequencies resonant with the magnetic drifts of the energetic electrons. Since low-frequency interchange instabilities preserve the electron's first and second adiabatic invariant, the wave-particle interaction is described with a two-dimensional phase-space that is directly observable. Deep modulations of the flux to gridded particle detectors are seen to be in agreement with numerical simulations [Warren and Mauel, 1995b]. They illustrate rotating "phase-space holes" that gradually move radially inward as the mode rotation frequency rises.



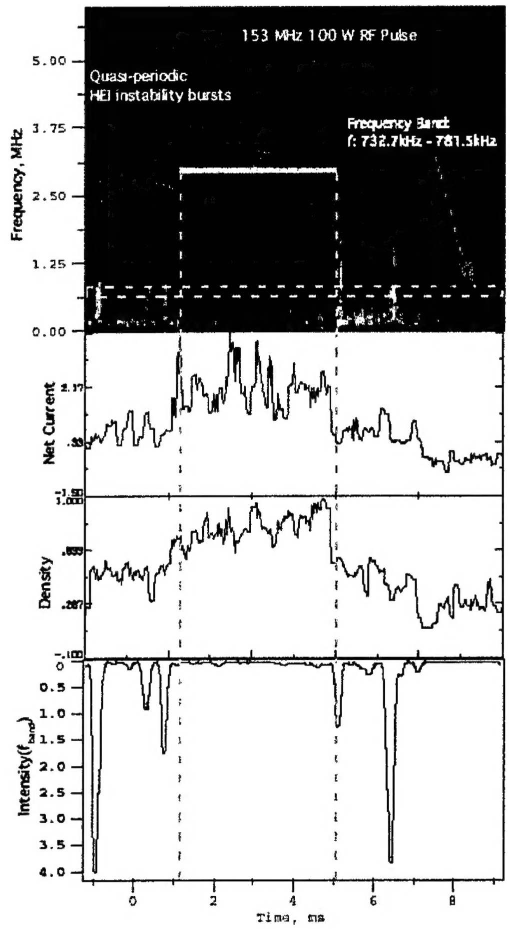
The nonlinear saturation of this instability changes dramatically when RF waves are applied to the plasma. We built and installed an $m = 3$ broad-band magnetostatic antenna at one of the poles of the Collisionless Terrella Experiment. (See figure to right.) It is constructed from 50 Ω copper coaxial cable and is terminated into a matched load. The antenna can be used to launch waves in the range of 1-1000 MHz. A broad-band amplifier with a peak output of 100 W is used to generate waves. The antenna can also excite cavity resonances of the vacuum vessel.

Typical experimental results are shown in the figure on the following page. Consistent with a nonlinear threshold, we found a minimum power was required before any appreciable effect on the dynamics of instability waves could be observed. In the figure, the results of 100 W applied at 153 MHz is shown. The top graph represents a fast floating potential signal plotted in a time/frequency domain (TFD). The bottom graph shows the intensity of the selected frequency band (732.7 to 781.5 kHz). Note the disappearance of the quasi-periodic instability bursts when the pulse is applied. This is accompanied by a bulk plasma density rise. When the pulse is switched off, the density returns rapidly to the plasma density before the pulse was ever applied and instability bursts reappear.

In general, it appears that the coherent phase of HEI mode, when frequency chirping is observed, can be suppressed by either boosting the gain of the pulse while keeping its width constant, or by increasing the width of the pulse while keeping its gain constant. It is important to note however, that there is some minimum gain and width requirement to cause any effect on the instability. For example, to suppress the HEI mode with a 100 W pulse, one needs to make it somewhere between 1.0 and 1.5 ms long

depending on when during the afterglow the pulse is applied (at the very onset of the instability, the mode is strong, and more power must be applied to suppress it).

To further examine plasma density increase when the RF wave is launched into the plasma, a Langmuir probe was moved to different radial positions, and radial density profile was obtained during the RF pulse. We observed an increase in plasma density localized near the core of the hot electron ring. Additionally, increased soft x-ray and photo-emission is observed during instability suppression. These indicate suppression of instability prevents re-distribution and transport of energetic electrons.



We are still testing and studying possible mechanisms that can explain the instability suppression. A fully developed model would enable us to evaluate applications of similar techniques to similar instabilities. For example, RF waves might be launched into the ionosphere to open a window of suppressed F-layer spread phenomena.

3. CURRENT ALONG MAGNETIC FIELD IN THE SOLAR ATMOSPHERE

Current flow along magnetic field lines that reach the corona are thought to drive solar storms. We have analyzed the implications of magnetic helicity conservation in the corona including the implications of the chaotic flows in the sun's convective zone. Together, these flows and helicity conservation lead to an exponetial increase in the parallel current. This suggests the possibility of energetic electron (*i.e.* "runaways") production as a possible contributor for coronal heating. Boozer 1999 presents further details.

4. Students Supported

This research has provided critical support for several students. Undergraduate student research interns gain valuable experience and "hands-on" skills with high-temperature plasma diagnostics. Graduate students use the laboratory and computational facilities as part of their educational and research activities.

During the past three years, undergraduate student research interns include: Andrew Chow, Dan Herrmann, Peter Leong, Dan Nichols, Ari Socrates, and Peter Steinvurze. Graduate student research assistants include: Susan Galayda, Ilya Joseph, Ben Levitt, Dmitry Maslovsky, and Shem Syed.

5. Summary

The research has enabled unique and significant tests of (1) the application of guiding center theory to large-scale transport of energetic plasma within a dipole magnetic field, (2) recent developments in nonlinear wave-particle dynamics, (3) self-consistent and nonlinear simulations of dipolar dynamics, (4) new theories of coronal heating, and (5) observations of new techniques to suppress interchange instabilities. Our research was motivated to understand the generation and transport of energetic particles found in laboratory, astrophysical and space plasmas. Our investigations combined laboratory experimentation, computer simulation, and plasma theory. We created an "artificial radiation belt" in the laboratory, allowing the creation and study of intense interchange instabilities. Recent measurements confirmed our self-consistent model for the nonlinear evolution of the interchange instability of hot plasma confined by dipolar magnetic fields. Additionally, we have discovered a mechanism to reduce the intensity of interchange instabilities by the application of high-frequency electromagnetic waves.

Several questions remain to be answered, and these are subjects of ongoing research. Building on the knowledge gained through this research, we are conducting new investigations using support from the DOE/NSF partnership in basic plasma science. This work aims to understand the nonlinear dynamics of strong interchange instabilities in rotating dipole-confined plasma and to observe, for the first time in a single experiment, interchange instabilities excited by magnetic curvature and driven plasma convection.

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8. "Suppression of Interchange Instabilities in a Magnetic Dipole using Boounce-Resonant RF Waves," D. Maslovsky, M. Mauel, B. Levitt, to be submitted to *Phys. Plasmas.*